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Wind energy potential in Liguria region

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ABSTRACT

In this work, the aim is to assess the current wind energy potential in the Liguria region, Italy, by the application of well assessed methodologies that are recalled within the paper. Data for a monitored period up to six and half years from 25 stations distributed over the four provinces of Liguria (i.e., La Spezia, Genoa, Savona and Imperia) have been analyzed.

From the data obtained on the 25 stations, only 4 of them seem to be eligible for energy production, but, due to other constraints such as environmental protected areas, only one of them seems the only one where the wind potential – which has been quite stable in the years – can be effectively exploited. However, as usual in these cases, also due to the complex orography of Liguria region, a monitoring campaign on the field should be additionally performed on the site.

Contents

1. Introduction

Italy is one of the countries that are currently using a large percentage of their import expenditures to purchase oil [1]. As it is widely known, the consumption of energy is one of the most reliable indicators of the development and quality of life reached by a country [2], which makes the necessity of satisfying a forecasted energy demand and ensure the provision of the energy needs. Thus, it may be strategically important to check the possibility that a part of the energy needs of Italy can be economically covered from renewable energy sources and mainly wind turbines energy. The assessment of the suitable regions for wind energy utilization and the estimation of the expected power production of wind turbines are a prerequisite for efficient wind turbines sitting under economical, social and environmental constraints [1]. The estimation of the wind turbines potential is generally related to a very long meteorological study of the measures of the wind speed.

According to the ENEA (Italian Agency for New Technologies, Energy and the Environment) Italy's renewable energy new installations decreased with respect to 2005, with 417 MW installed in 2006 against 453 MW installed the previous year [3], for an overall energy production in 2006 of 2123.4 MW [3].

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According to the ANEV (National Wind Power Association), Italy's total installed capacity should reach 9500 MW in 2012 if the government wants to provide the resources necessary to reach the objective that it set: a 25% renewable origin electricity share beginning in 2012 [3].

Several studies have been developed in order to more understand the wind power plant in Italy, the principal aim of the study made by [4] is to make a pre-evaluation concerning the possibility of installing wind turbines in a Salina island. Thus, the application of multi-criteria methods so as to support the selection and the evaluation of one or several suggested solutions, after having analyzed the local conditions of the environment and of its energetic profile [4].

In Sicily (Italy), the wind measures as recorded from several stations have been used to model the overall wind field in the region [5]. A statistical analysis of the wind data has allowed the estimation of the parameter of a probabilistic distribution function described, as usual in this domain, by a Weibull's function. Based on a preliminary study, an original approach integrating artificial neural networks and geostatistic techniques [5] has been developed in order to define the map of the wind speed of the region at 10 and 50 m above the ground level [5].

The study made by [1] – based on measures performed in the stations having a long series in continued time – has marked the presence of considerable wind power resources in the areas near to shore, on the mountains and hill summits. Actually, the annual average flows of wind turbines energy has been calculated and perceived as being rather high (above 600 W/m^2 year to 30 m) in these zones, which in fact probably makes Liguria a candidate for the use of wind power plants [1].

Situated in Northwest Italy, the Liguria region covers a territorial area of about 5100 km^2. It creates an important gulf in the Mediterranean Sea [1]. Its landscape is dominated by the mountains of the Maritime Alps. These mountains can reach 2200 m in the Alps and about 1700 m in the Apennines. Liguria has a mild climate due to its position close to the sea. Moreover, the sea favours important interactions between the movements of air masses with the orography [1]. The identification of the

Table 1
The RMSE, K–S, and Chi-square values for SD and LS identification methods.

Sites	Method	C	K	$D_{0.10}$	D^*	$D_{0.10}-D^*$	RMSE	χ^2
(a)								
Borgonuovo	SD	1.30	2.30	0.7946	0.1775	0.6170	7.4960E−003	6.0353E−005
	LS	1.33	2.36	0.7942	0.2619	0.5322	1.0414E−002	1.1649E−004
Capo Vado	SD	7.18	1.43	0.7949	0.1151	0.6798	8.553E−003	7.8577E−005
	LS	7.53	1.63	0.7947	0.1535	0.6412	1.2287E−002	1.6217E−004
Castellari	SD	1.32	1.10	0.7925	0.6149	0.1775	2.6406E−002	7.4895E−004
	LS	1.45	1.13	0.7924	0.6313	0.1611	2.6737E−002	7.4931E−004
Cenesi	SD	1.70	1.43	0.7950	0.0850	0.7100	3.5161E−003	1.3278E−005
	LS	1.70	1.20	0.7944	0.2118	0.5826	1.0975E−002	1.2939E−004
Corniolo	SD	2.85	1.09	0.7947	0.1626	0.6320	8.2062E−003	7.2330E−005
	LS	2.72	1.06	0.7946	0.1868	0.6077	1.0035E−002	1.0816E−004
Fontana Fresca	SD	5.51	1.48	0.7946	0.1809	0.6136	8.9827E−003	8.6666E−005
	LS	5.57	1.45	0.7945	0.1881	0.6064	9.6895E−003	1.0084E−004
(b)								
Genova Cambiaso	SD	2.12	1.63	0.7934	0.4250	0.3684	1.7015E−002	3.1098E−004
	LS	2.30	1.50	0.7925	0.6088	0.1836	2.3930E−002	6.1509E−004
Giacopiane Lago	SD	3.82	1.06	0.7941	0.2719	0.5222	1.2364E−002	1.6420E−004
	LS	4.56	1.14	0.7939	0.3290	0.4648	1.6654E−002	2.9792E−004
Monte Maure	SD	4.32	1.69	0.7944	0.2256	0.5687	1.2651E−002	1.7192E−004
	LS	4.83	1.84	0.7941	0.2733	0.5207	1.678E−002	3.0269E−004
Monte Rocchetta	SD	4.21	1.48	0.7942	0.2670	0.5271	1.2381E−002	1.6465E−004
	LS	4.5	1.66	0.7939	0.3202	0.4736	1.5146E−002	2.4641E−004
Monte Settepani	SD	6.13	1.84	0.7945	0.1935	0.6009	7.8714E−003	6.6549E−005
	LS	5.75	1.72	0.7941	0.2886	0.5054	1.1737E−002	1.4796E−004
Poggio Fearza	SD	5.23	1.51	0.7947	0.1542	0.6405	9.3693E−003	9.4286E−005
	LS	5.56	1.74	0.7945	0.2020	0.5924	1.0749E−002	1.2411E−004
(c)								
Polanesi	SD	1.37	2.31	0.7933	0.4520	0.3412	2.2104E−002	5.2477E−004
	LS	1.40	2.46	0.7929	0.5332	0.2596	2.3555E−002	5.9596E−004
Pornassio	SD	1.39	1.92	0.7930	0.5147	0.2782	2.3927E−002	6.1494E−004
	LS	1.48	1.95	0.7922	0.6749	0.1172	3.1611E−002	1.0732E−003
Ranzo	SD	2.65	2.23	0.7953	0.0371	0.7581	1.8279E−003	3.5887E−006
	LS	2.94	2.5	0.7936	0.3854	0.4082	1.7750E−002	3.3843E−004
Romito Magra	SD	1.10	1.38	0.7942	0.2689	0.5252	9.5543E−003	9.8048E−005
	LS	1.11	1.26	0.7930	0.5046	0.2883	1.7670E−002	3.3538E−004
Casoni	SD	6.34	1.43	0.7947	0.1566	0.6381	9.0777E−003	8.8510E−005
	LS	5.90	1.32	0.7942	0.2656	0.5285	1.1447E−002	1.4074E−004
Imperia	SD	3.72	1.54	0.7944	0.2118	0.5826	9.9875E−003	1.0714E−004
	LS	3.73	1.51	0.7944	0.2223	0.5720	1.0619E−002	1.2113E−004

Table 2
The average wind speed on the whole measurement period for each site.

Sites	Measurement period	Wind speed (m/s) 10 (m)	Wind speed (m/s) 40 (m)	*K* (SD)	*C* (m/s) (SD)
Borgonuovo	2003-6/2008	1.15	1.86	2.3	1.3
Capo Vado	2006-6/2008	6.52	8.56	1.43	7.18
Castellari	2003-6/2008	1.28	2.06	1.10	1.32
Cavi di Lavagna	2003-6/2008	1.25	2.03	0.98	1.24
Cenesi	2003-6/2008	1.55	2.42	1.43	1.70
Corniolo	1/2008-6/2008	2.76	4.05	1.09	2.85
Fontana Fresca	2004-6/2008	5.00	6.76	1.48	5.51
Genova Centro funzionale	2007-6/2008	3.64	5.14	1.29	3.94
Genova Villa Cambiaso	2002-2006	1.90	2.89	1.63	2.12
Giacopiane Lago	2005-6/2008	3.73	5.28	1.06	3.82
La Spezia	1/2008-6/2008	3.15	4.51	1.43	3.47
Levanto-S Gottardo	2003-6/2008	1.48	2.32	1.46	1.63
Monte Maure	2004-6/2008	3.86	5.38	1.69	4.32
Monte Rocchetta	2003-6/2008	3.80	5.33	1.48	4.21
Monte Settepani	2004-6/2008	5.45	7.29	1.84	6.13
Poggio Fearza	2007	4.72	6.44	1.51	5.23
Polanesi	2003-6/2008	1.21	1.95	2.31	1.37
Pornassio	2005-6/2008	1.24	1.98	1.92	1.39
Ranzo	2004-6/2008	2.35	3.48	2.23	2.65
Romito Magra	2004-2006	1.01	1.66	1.38	1.10
Savona Istituto Nautico	4/2007-6/2008	3.47	4.90	2.44	3.91
Vernazza	2004-2007	1.65	2.55	1.84	1.85
Casoni	2002-6/2008	5.74	7.30	1.43	6.34
Diano Castello	2003-2007	0.69	1.20	0.99	0.69
Imperia	2003-6/2008	3.35	4.77	1.54	3.72

appropriate areas to install wind turbines is particularly difficult because of the narrow territory that is available between the sea and the mountains, and because of the presence of some plates of short valleys in which urban settlements (along the coast) are placed in a non-homogeneous way.

In this work, the aim is to assess the current wind energy potential in the Liguria region, by the application of well assessed methodologies that are recalled within the paper.

2. The wind power plants and its impact on the environment

From an environmental viewpoint, a recent study [6] has quantitatively assessed the impact of wind power generation on the living of some animals. However, the environmental impact of wind power generation includes several other aspects which should be taken into account according to a cost benefit analysis with respect to other technologies for energy production.

More generally, in recent decades, some key topics such as sustainability, weather conditions, climate changes, environmental protection and security of energy supplies have been widely debated at an academic and political level [7]. The majority of countries are making efforts to increase the efficiency of production, reducing the dependence of imports and trying to avoid the negative effects on the environment through the optimization of energy uses [7]. The renewable energy seems to be the suitable way to solve these problems.

Table 3
Available wind energy for each site.

Sites	*K*	*C* (m/s)	Power density (W/m^2)	Available energy (MWh/m^2 year)	Altitude (m)	Latitude N	Longitude E
Borgonuovo	2.3	1.3	1.54	13.6	100	43.8463	7.6208
Capo Vado	1.43	7.18	487.7	4271.7	170	44.2583	8.4425
Castellari	1.10	1.32	6.04	52.9	100	44.1456	8.2625
Cavi di Lavagna	0.98	1.24	7.5	65.7	100	44.2961	9.3739
Cenesi	1.43	1.70	6.47	56.7	110	44.0750	8.1347
Corniolo	1.09	2.85	62	543.5	258	44.1063	9.7348
Fontana Fresca	1.48	5.51	206.5	1809.3	743	44.4022	9.0936
Genova Centro funzionale	1.29	3.94	100	874.3	20	44.4017	8.9472
Genova Villa Cambiaso	1.63	2.12	9.90	86.7	40	44.3986	8.9633
Giacopiane Lago	1.06	3.82	161.75	1417	1016	44.4608	9.3875
La Spezia	1.43	3.47	54.47	477.2	5	44.1045	9.8075
Levanto-S Gottardo	1.46	1.63	5.5	48	100	44.1811	9.6211
Monte Maure	1.69	4.32	80	694.5	210	43.7922	7.6192
Monte Rocchetta	1.48	4.21	92	805.2	412	44.0755	9.9197
Monte Settepani	1.84	6.13	203	1776.5	1375	44.2430	8.1966
Poggio Fearza	1.51	5.23	170	1483.5	1833	44.0420	7.7935
Polanesi	2.31	1.37	1.8	15.8	50	44.3658	9.1247
Pornassio	1.92	1.39	2.3	19.8	500	44.0639	7.8664
Ranzo	2.23	2.65	13.5	118	310	44.0632	8.0049
Romito Magra	1.38	1.10	2	16.9	100	44.1033	9.9303
Savona Istituto Nautico	2.44	3.91	40.23	352.4	38	44.3056	8.4855
Vernazza	1.84	1.85	5.61	49.2	160	44.1361	9.6833
Casoni	1.43	6.34	332.5	2908.8	800	44.5272	9.3086
Diano Castello	0.99	0.69	1.20	10.5	135	43.9232	8.0669
Imperia	1.54	3.72	59	516.7	10	43.8882	8.0416

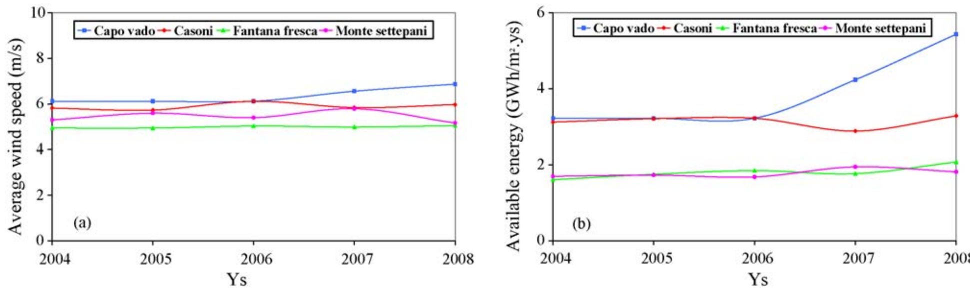

Fig. 1. For the four sites with highest wind speeds: (a) annual variation of average wind speed and (b) annual variation of the available energy.

Renewable energy resources are more and more in demand all over the world because of the concerns about the availability of fossil fuels, the rise of oil prices, air pollution and global warming [8]. Among the available renewable energy sources, wind energy represents a great challenge because its recent technological advances have reduced the costs and made it competitive with respect to conventional energy sources [8]. The development of energy technologies that are environmentally friendly has been accelerated in response to the growing concerns about the impacts on climate change [9]. However, the wide diffusion of these technologies could be limited by the absence of appropriate political decisions [9].

Wind energy is a clean energy source which produces no emissions that cause acid rain or greenhouse gases, such as non-polluting power plants that use fossil fuels such as coal or natural gas [6]. Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where the best sites can be found [6]. However, it is convenient to keep in mind that a part from renewable energy which wind power plant, there is no energy production without producing toxic emissions, mutagenic or carcinogenic.

We can sum up the impact of wind power plant that have been detected so far, essentially in their aesthetic impact, the noise generated by the rotation of the rotor blades and the danger that may in some cases the turbines running on life bird [6]. Regarding noise, considerable efforts have been made in order to reduce it to a lower level. Indeed, progress in recent years in the design profiles of blades have substantially reduced the original aerodynamic noise, while the mechanical noise has been greatly reduced with the advent of the new generation of turbines operating without gearbox. Nowadays, the sound level of a wind turbine does not exceed 40 dB [10]. As for the impact of wind turbines on birds, there is always controversy between studies condemning the wind and those which reduce that impact.

3. Wind data used in this study

The estimation of a potential is based on the knowledge of wind regimes on the considered territory. The accuracy of this phase is crucial as the provided power is proportional to the cube of wind speed. In this work, the assessment of the Liguria region wind potential has been carried out. In total, data from 25 stations distributed over the four provinces of Liguria (i.e., La Spezia, Genoa, Savona and Imperia) have been analyzed.

The data used in this current study were observed in the following locations:

- Casoni (2002–June/2008),
- Borgonuovo, Castellari, Cavi di Lavagna, Cenesi, Imperia, Levantos Gottardo, Monte Rocchetta and Polanesi (2003–June/2008),
- Genova villa Cambiaso (2002–2006),
- Diano Castello (2003–2007),
- Monte Settepani, Fontana Fresca, Monte Maure and Ranzo (2004–June/2008),
- Vernazza (2004–2007),
- Giacopiane Lago and Pornassio (2005–June/2008),
- Romito Magra (2004–2006),
- Capo Vado (2006–June/2008),
- Genova, ARPAL functional center (2007–June/2008),
- Savona (April/2007–June/2008), Poggio Fearza (2007),
- Corniolo and La Spezia (2008–June/2008).

The data have been used to evaluate the annual frequency of wind speed, the monthly and annual variations as regards average speed, the vertical profile of the wind speed, and the assessment of potential wind power.

4. Modelling frequencies of wind speed

In the literature, there are several probability density functions (PDF), which can be used to describe the wind speed data. The most commonly used PDF is the Weibull function [11]. Recently, the Weibull's distribution was also considered useful and appropriate for wind energy as it is one of the easiest methods used to identify the wind potential of a specific site, since it allows to estimate the probability density function just with two parameters namely c and k [12]. In addition, the Weibull's distribution allows us to have a reasonable adjustment of these two parameters when the monitored wind speed values are at a different height (for example 10 m) with respect to the desired height of the wind power plant hub (for example 40 m) [11].

The Weibull probability density function has the following form [13,14]:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{1}$$

Table 4
Annual average wind speed (a), annual power density (b) and annual available energy for the four sites with highest wind speeds.

	Capo Vado	Casoni	Fontana Fresca	Monte Settepani
(a) Annual average wind speed (m/s)				
2004	–	5.82	4.94	5.30
2005	–	5.73	4.94	5.60
2006	6.12	6.12	5.03	5.40
2007	6.56	5.84	4.99	5.79
2008	6.87	5.97	5.04	5.16
(b) Power density (W/m^2)				
2004	–	355.98	183.80	194.02
2005	–	366.41	200.16	197.92
2006	367.58	367.59	211.40	192.09
2007	483.58	329.03	202.04	222.72
2008	620.71	374.64	237.08	207.54
(c) Available wind energy (GWh/m^2 year)				
2004	–	3.12	1.61	1.70
2005	–	3.21	1.75	1.73
2006	3.22	3.22	1.85	1.68
2007	4.24	2.88	1.77	1.95
2008	5.44	3.28	2.08	1.82

where $f(v)$ is the probability of observing wind speed (v), k is the dimensionless Weibull shape parameter (or factor) and c is the Weibull scale parameter.

4.1. Estimation methods

In this study, the two parameters of the Weibull probability density functions have been determined by the standard deviation (SD) and least squares (LS) methods.

In the SD method, two parameters of the Weibull probability density functions k and c can be related to the mean speed V_m and standard deviation σ [14,15]:

$$V_m = \int_0^\infty v\, f(v)\, dv = \int_0^\infty v \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^K}\, dv = c\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

where

$$\Gamma(y) = \int_0^\infty e^{-x} x^{y-1}\, dx \tag{3}$$

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \tag{4}$$

$$c = \frac{V_m}{\Gamma(1+(1/k))} \tag{5}$$

The LS method consists of identifying Weibull's parameters according to the minimisation of the sum of square of residues. A detailed description can be found in [16,17].

4.2. Model selection criteria

The following model selection criteria have been used to decide the most appropriate model (SD and LS) for explaining the distribution of a statistical data: the root mean square error (RMSE), Chi-square (χ^2) and the Kolmogorov–Smirnov test (K–S).

The best distribution can be determined according to the lowest values of those criteria. The test of K–S is used to decide which of the methods adopted approximates the measures with the highest level of significance. It sets the null hypothesis H0 that the histogram follows a Weibull distribution with shape and scale parameters known.

The value of the test statistic, D for all "n" intervals can be expressed as:

$$D = Max|\, f(v,c,k) - f_n(v)| \tag{6}$$

In this work, the significance level chosen is 10%, this means that the likelihood of the presence of initial rejection is 10%. The critical parameter $D_{0.10}$ for the significance level is given by:

$$D_{0.10} = 0.8324905 - \frac{0.199103}{\sqrt{n}} - 0.026511D + 0.002725911D^2 \tag{7}$$

The parameter D for the number of "n" intervals is given by:

$$D^* = D\sqrt{n} \tag{8}$$

If the value of D^* will be greater than the value of the critical parameter $D_{0.10}$, the initial hypothesis is refused.

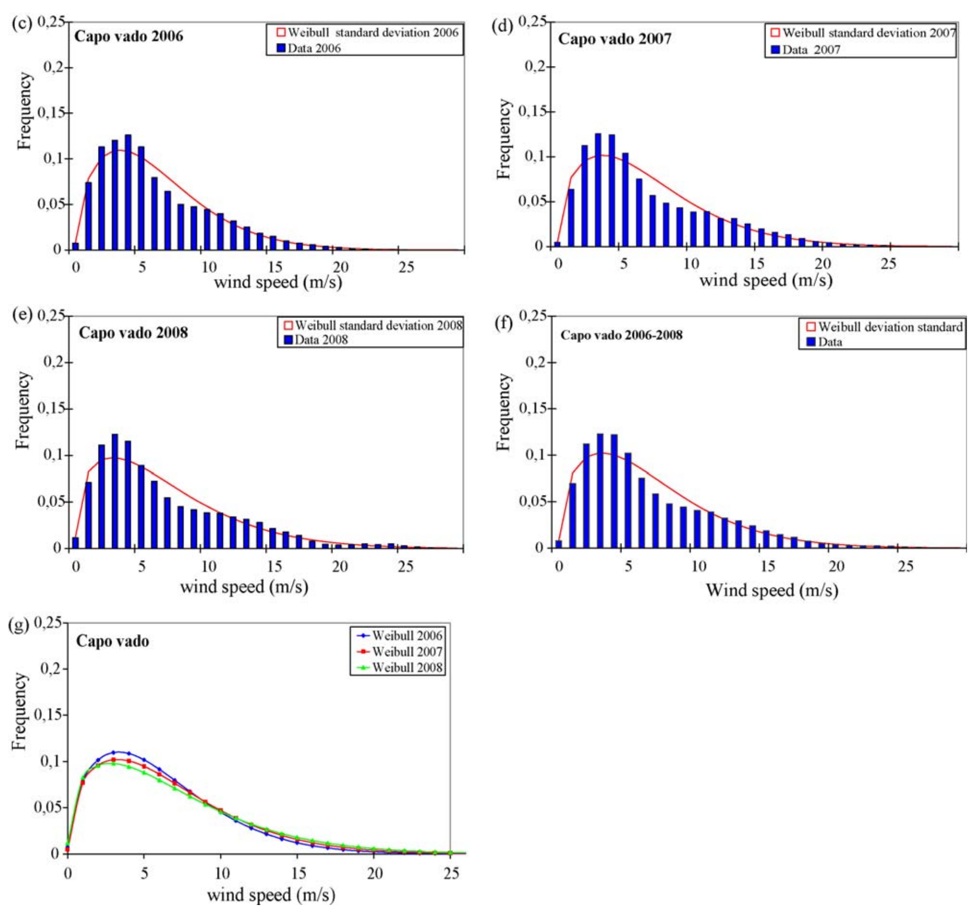

Fig. 2. The frequency histogram of the wind speed for Capo Vado (the site with highest average wind speed).

5. Power available in the wind

The power of the wind that flows at speed v through a blade sweep area A increases as the cubic of its velocity and is given by [18]:

$$P(v) = \frac{1}{2}\rho A v^3 \tag{9}$$

where ρ is density of air.

The wind power density of a site based on Weibull's probability density function can be expressed as follows [18]:

$$\frac{P}{A} = \int_0^\infty P(v)\, f(v)\, dv = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \tag{10}$$

Once wind power density of a site is given, the wind energy density for a desired duration can be calculated as [18]:

$$\frac{E}{A} = \frac{T}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \tag{11}$$

where T is the time period.

It is interesting to calculate the air density as it follows the law of Boyle [16]:

$$\rho = \frac{MP}{RT} \ \ (\mathrm{kg/m}) \tag{12}$$

M: molecule weight (kg/mol); P: pressure (N/m); R: universal gas constant = 8.31434 (J/mol K); T: temperature (K).

5.1. Extrapolation at the hub height

There are several methods of extrapolating Weibull's parameters c and k directly. The most currently used is the one given by Justus et al. [11]:

$$c(z) = c_1 (z/z_1)^{\alpha} \tag{13}$$

$$k(z) = k_1 \frac{[1 - 0.088\ln(z_1/10)]}{[1 - 0.088\ln(z/10)]} \tag{14}$$

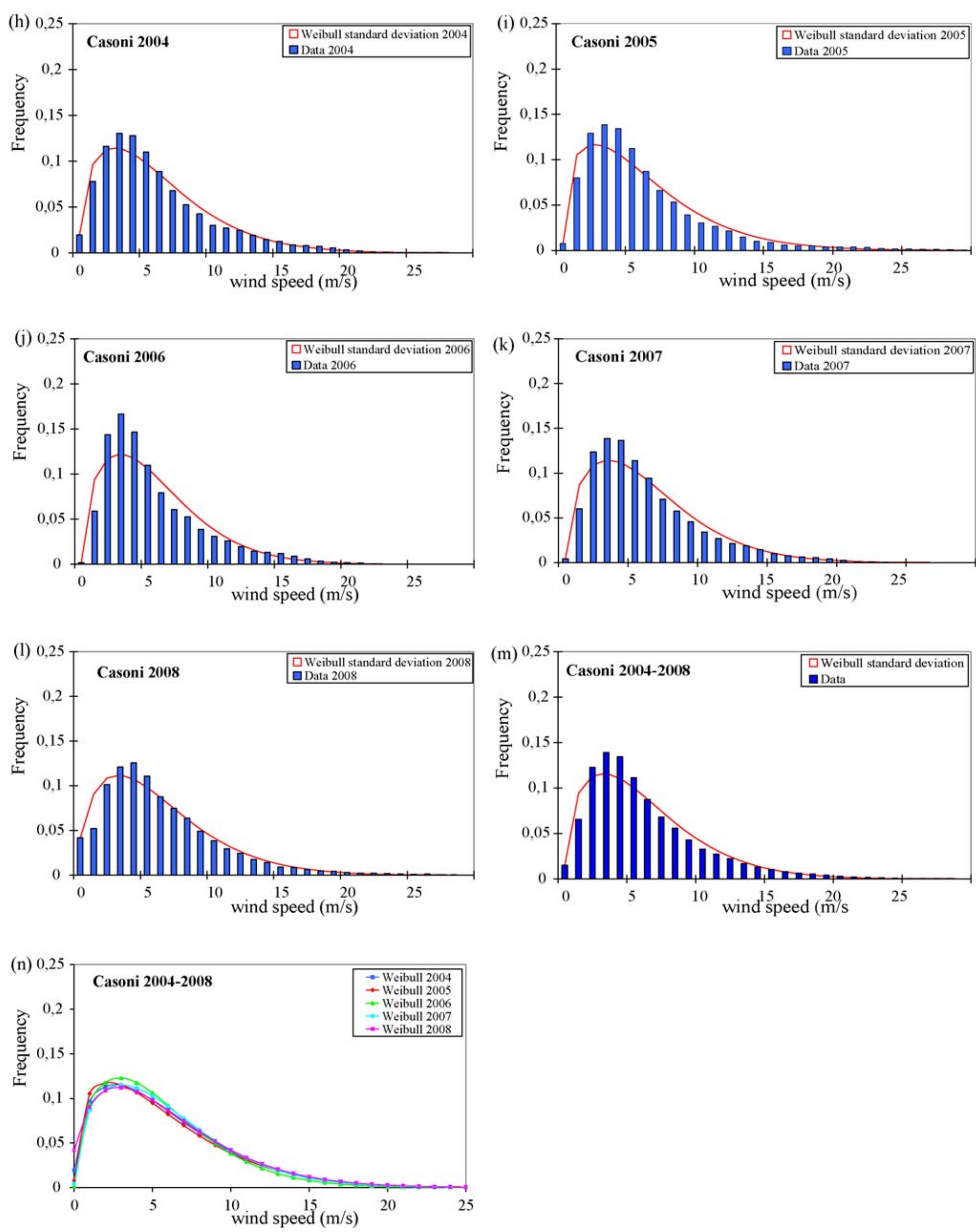

Fig. 3. The frequency histogram of the wind speed for Casoni (the site with second highest average wind speed).

The exponent of the power law is given by [11]:

$$\alpha = \frac{[0.37 - 0.088 \ln c_1]}{[1 - 0.088 \ln(z_1/10)]} \quad (15)$$

The knowledge of wind speed at heights between 20 and 120 m above ground level is highly desirable for any decision about the localization, the sizing, and the technology choice of wind turbines [16]. Often, these data are not available and some interpolation should be performed on the basis of the wind speed measured at 10 m [16]. This requires a law to predict the wind speed at a height (z), from the speed measured at a lower height (z_1), which is usually the height of the anemometer. This law is given by [18]:

$$\frac{v(z)}{v(z_1)} = \left(\frac{z}{z_1}\right)^{\alpha} \quad (16)$$

where $v(z)$ is the wind speed estimated at the desired height z, $v(z_1)$ is the wind speed at the height z_1 and α is the coefficient of power law.

6. Ordinary Kriging

The Kriging method is named in honour of Dr. Kriging, a noted South African mining geologist. With this method, he made estimates from a specified number of adjacent data with considering the interdependence expressed in a variogram [19]. In recent years, the method has been widely applied in different research fields, among which the application in geographic information systems in order to interpolate data. According to Bargaoui and Chebbi [20], the most classical method in the Kriging of environmental data is to operate with spatial lags by using spatial coordinates (X,Y) of data locations. The most frequently used form is ordinary Kriging (OK). OK is established on the basis of the variogram function which represents the spatial data variability. According to Lloyd and Atkinson [21], Bargaoui and Chebbi [20], the principal tool of geostatistical analyses is the variogram. It can be defined as half the expected squared difference between paired random functions

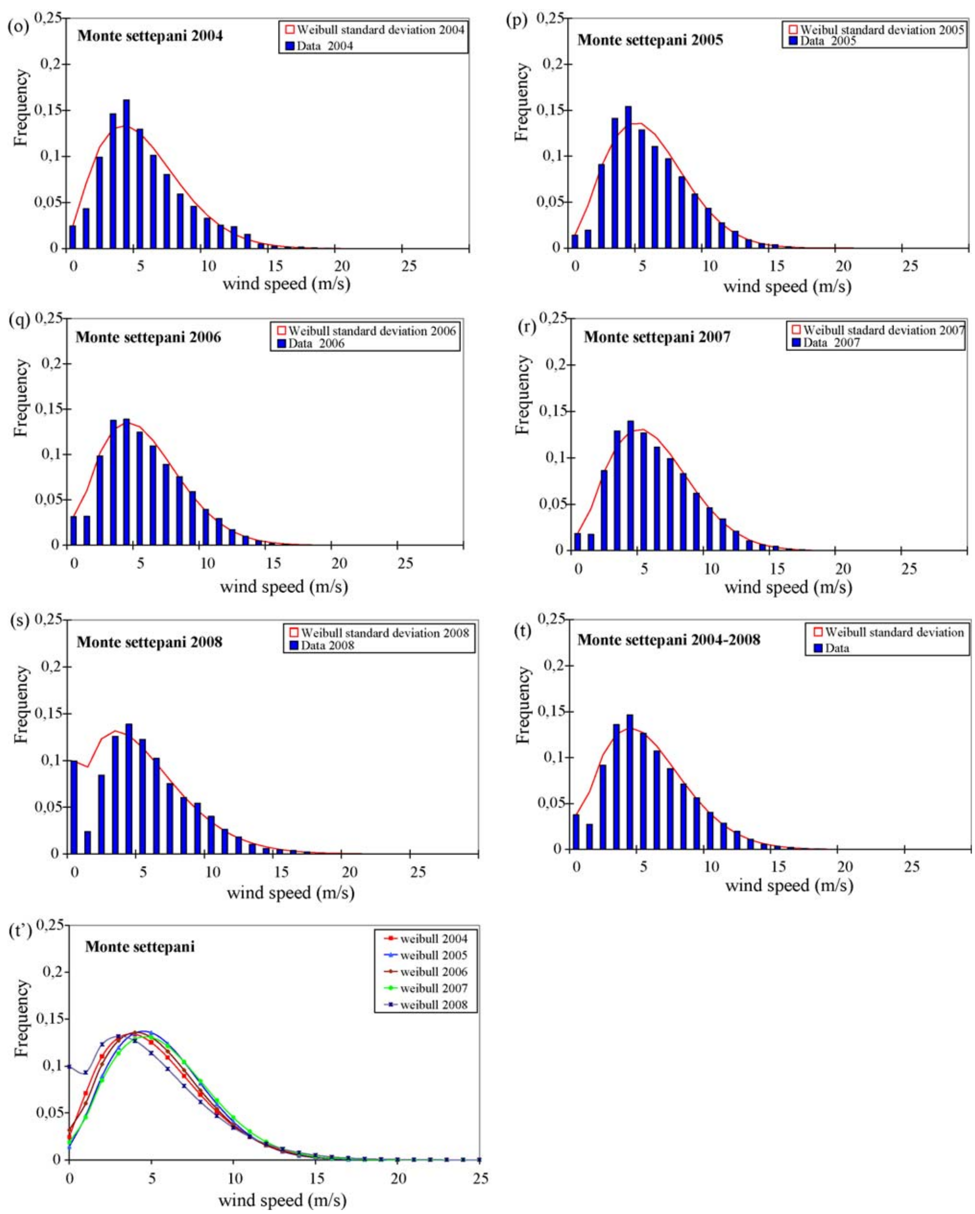

Fig. 4. The frequency histogram of the wind speed for Monte Settepani (the site with third highest average wind speed).

separated h:

$$\gamma(h) = \frac{1}{2}E[\{z(x) - z(x+h)\}^2] \quad (17)$$

where h is distance vector and x is location vector.

Lloyd and Atkinson [21] concluded that Kriging is a form of weighted average estimator. The weights are assigned on the basis of a model fitted to a function, such as the variogram, which represents spatial structure in the variable of interest. OK estimates are linear weighted moving averages of the n available observations over the support w:

$$z^*(w) = \sum_{i=1}^{n} \lambda_i z(x_i) \quad (18)$$

where λ_i is the weights assigned to the available observations and w is the support over which the estimate is made.

The weights sum is equal to one in order to satisfy the unbiased estimation:

$$\sum_{i=1}^{n} \lambda_i = 1 \quad (19)$$

The estimation variance is the expected value of the squared difference between $z^*(x_0)$ and $z(x_0)$ [21]:

$$\sigma^2 = E\{[z^*(x_0) - z(x_0)]^2\} \quad (20)$$

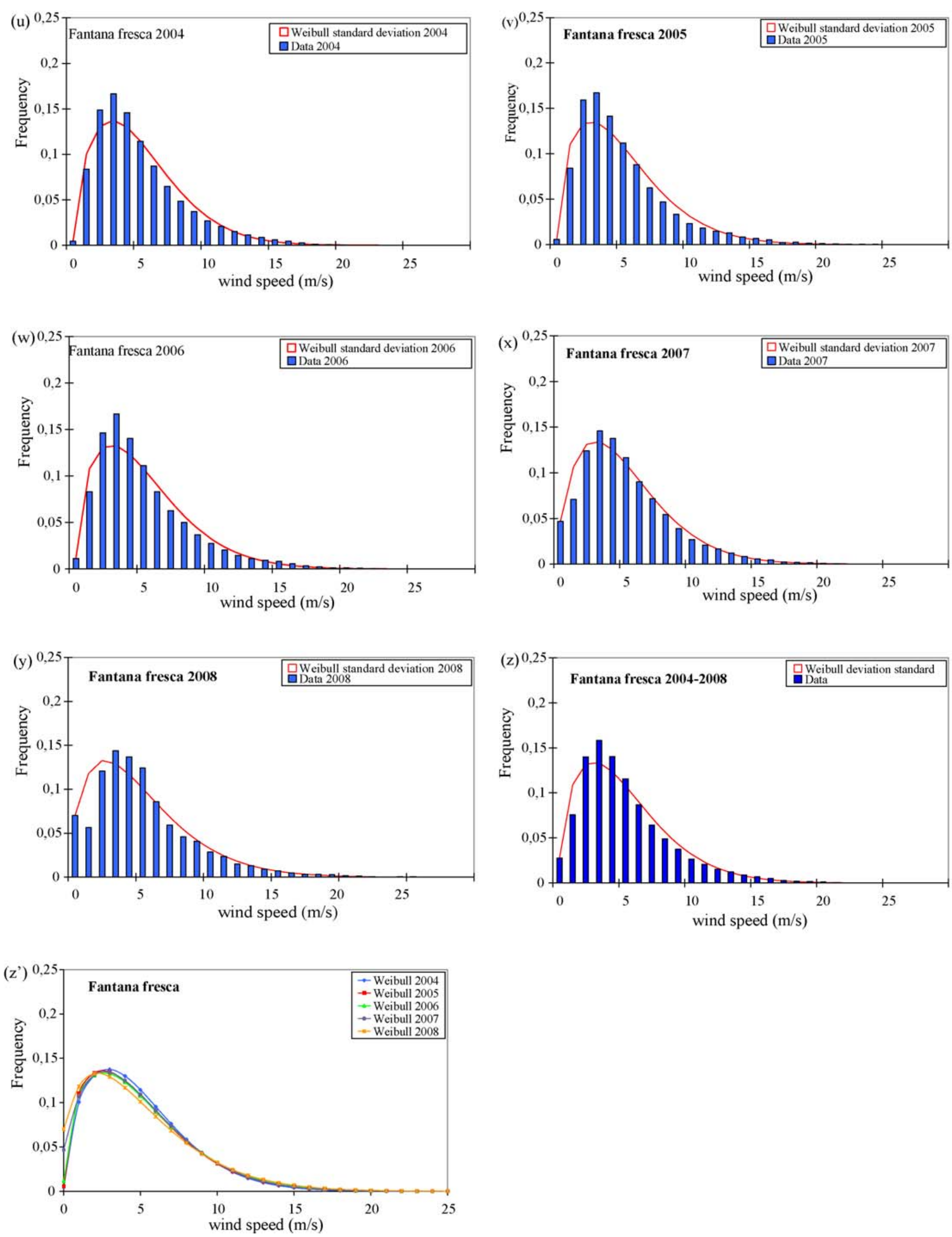

Fig. 5. The frequency histogram of the wind speed for Fontana Fresca (the site with the fourth highest average wind speed).

The estimation variance is minimised with the addition of Lagrange multiplier, ψ, [21]:

$$\sigma_k^{*2} = \sum_{i=1}^{n} \lambda_i \bar{\gamma}(x_i, w) + \psi - \bar{\gamma}(w, w) \tag{21}$$

where $\bar{\gamma}(x_i, w)$ is the average semivariance between the sample point i and the block w, and $\bar{\gamma}(w, w)$ is the within-block variance.

In this work, Kriging has been used to produce qualitative wind and energy maps for Liguria region.

7. Results and discussions

The RMSE, K–S and Chi-square values for SD and LS identification methods are given in Table 1. The comparison of the RMSE and χ^2 values indicates that the Weibull probability distribution function based on SD demonstrate a better fit than the Weibull based on LS.

According to K–S test (Table 1), distributions approximate with good level of significance theoretical measurements to the experimental ones, because the setting D^* is always lower than the values of critical significance level chosen. It was verified that the best method of estimation is the method of SD because this method has increased the difference between $D_{0.10}$ and D^*.

The obtained results from the available meteorological data used in this study show that in some sites the wind energy potential is low, while in other sites wind potential is considerably high. With the aim of covering all four provinces of Liguria, we used data from all the available stations, even if most of them are not located in the windiest parts of the territory.

The average wind speed (on the whole measurement period) has been evaluated for each site and shown in Table 2. The results

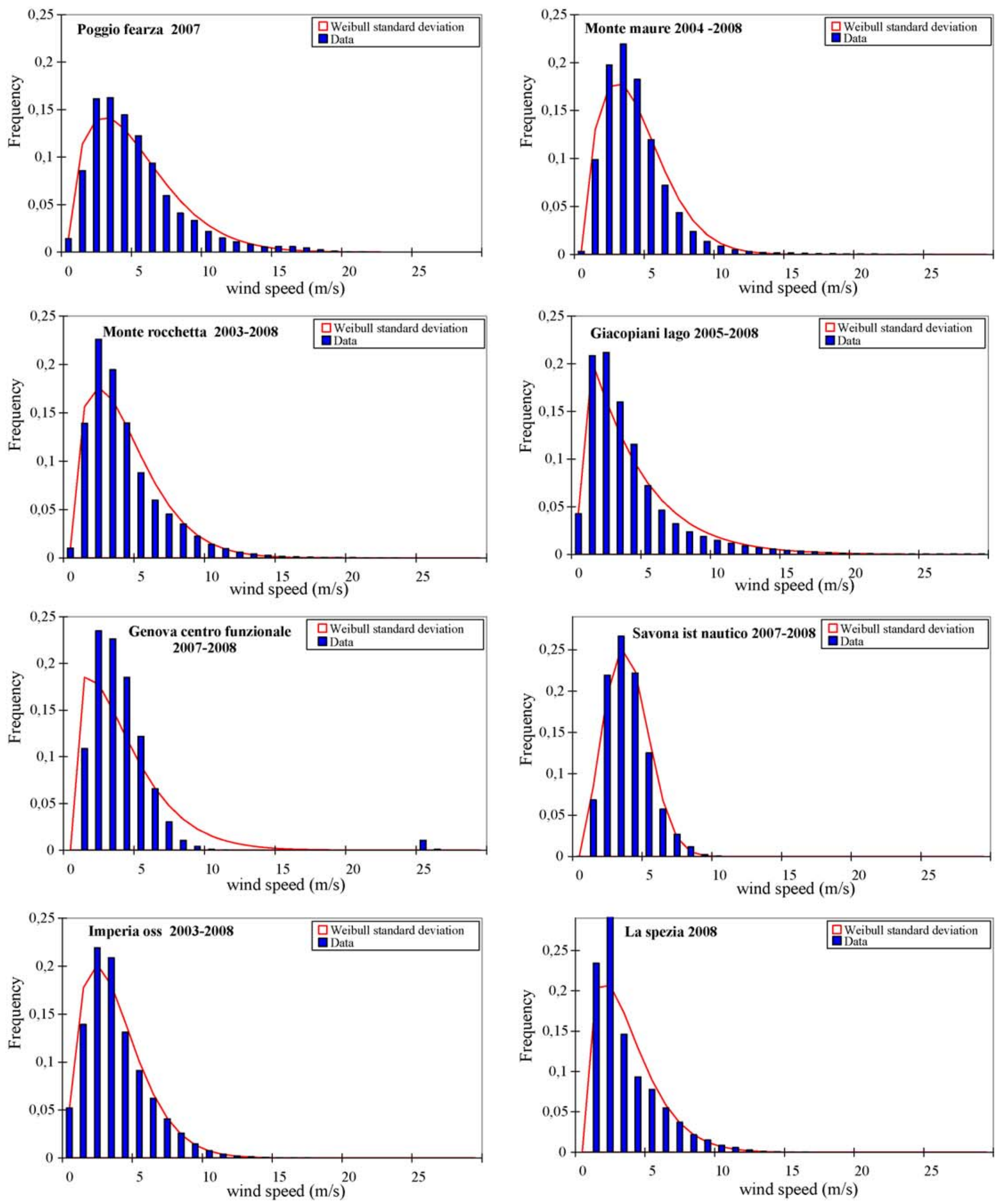

Fig. 6. The frequency histogram of the wind speed for all the sites, apart from the ones shown in Figs. 2–5.

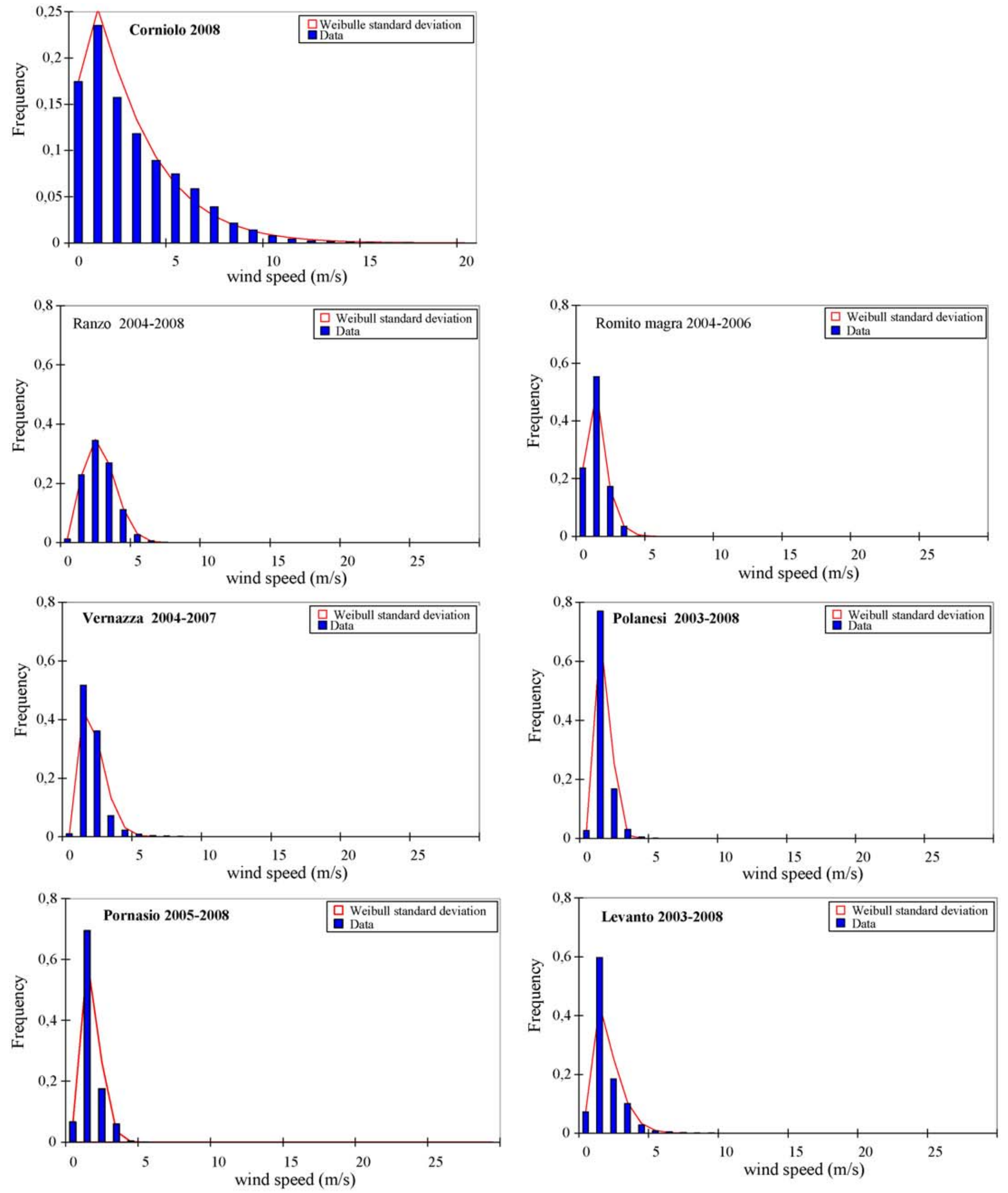

Fig. 6. (*Continued*).

show that Capo Vado (6.52 m/s), Casoni (5.74 m/s), Monte Settepani (5.45 m/s) and Fontana Fresca (5 m/s), have the highest wind speeds. Unlike other sites, among these four sites (Table 3) Capo Vado is considered the most promising site for the Liguria region with an available energy of 4271.7 MWh/m^2 year. Fig. 1(a) shows the annual variation of average wind speed of each of these sites (see Table 4(a)). For Capo Vado, a minimum average speed of 6.12 m/s in 2006 and a maximum of 6.87 m/s in 2008, have been monitored, which show that the average wind speed of the site has not undergone considerable changes and has kept the same order of magnitude. The same conclusion can be drawn for Casoni with a minimum of 5.73 m/s in 2008 and a maximum of 6.12 m/s in 2006, and for Monte Settepani with a minimum of 5.16 in 2008 and a maximum of 5.79 m/s in 2007. Similar results are obtained for Fontana Fresca with a minimum of 4.94 m/s in 2004 and a maximum of 5.04 m/s in 2008. The annual variation of the available energy is reported in Fig. 1(b), see also Table 4(c).

The frequency histograms of the wind speed are determined and reported in Figs. 2–6, with a range of speeds [0–20 m/s], for Capo Vado, Casoni, Monte Settepani and Fontana Fresca, while for the other sites it has been used a range of speed between [0–10 m/s] and [0–5 m/s]. On the basis of these results, a more detailed study has been performed on the four sites in which a considerable wind speed has been observed. For Capo Vado, an annual adjustment of the frequency of wind speed data has been performed on the basis of the knowledge of the Weibull's probability distribution function (whose parameters are determined using the identification by means of SD). The study shows that the behaviour profile frequency of the wind speed is the same for 2006, 2007, 2008 and also for the period 2006–2008, (Fig. 2(f), see also, Fig. 2(g)), which presents a comparison between the Weibull's distributions obtained for each year.

In conclusion, it can be assessed that Capo Vado site presents regular wind behaviour during the considered time horizon. The

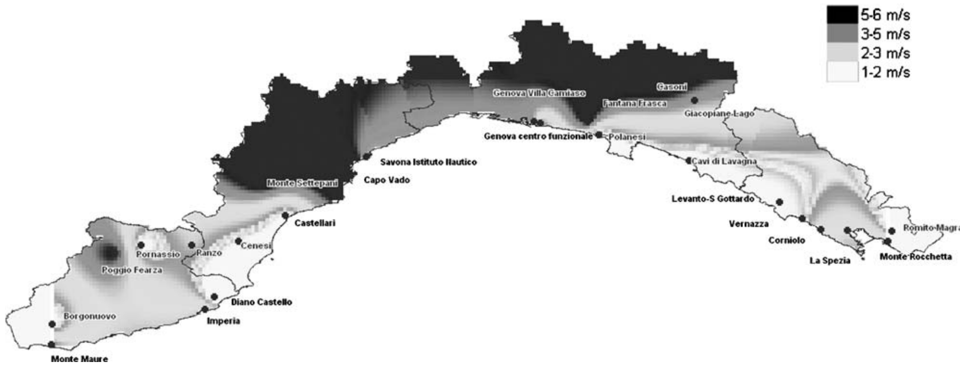

Fig. 7. The average wind speed map at 10 m as obtained by Kriging on the set of data.

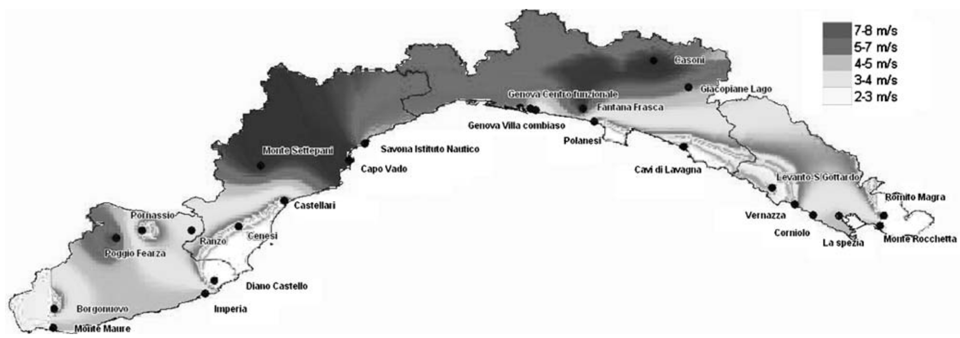

Fig. 8. The average wind speed map at 40 m as obtained by Kriging on the set of data.

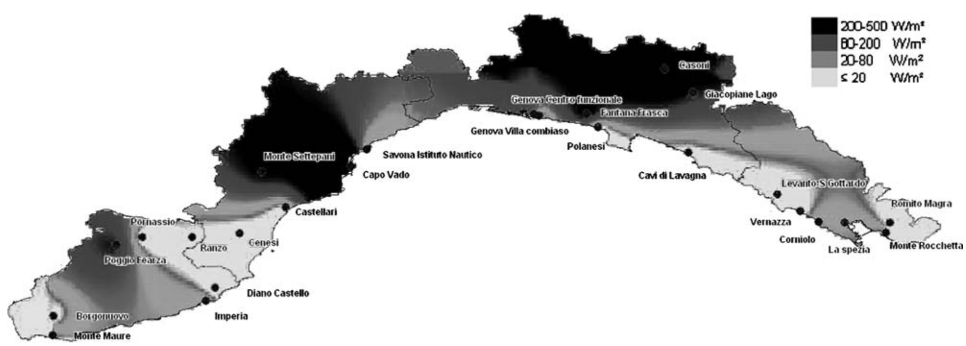

Fig. 9. The average wind power density map at 10 m as obtained by Kriging on the set of data.

same considerations can be drawn for Casoni (Fig. 3(h–n)), Monte Settepani (Fig. 4(o–t′)) and Fontana Fresca (Fig. 5(u–z′)). The wind speed histograms of the other sites have been determined and presented in Fig. 6, and show that the highest probability of occurrence for wind speeds is between 0 and 3 m/s, which restrict the use of wind turbines for the production of electricity in these regions.

The data from all the sites have been finally given as input to a Kriging algorithm in order to produce maps of the wind speed at 10 m, at 40 m, and a map of the wind potential at 10 m, shown in Figs. 7–9.

8. Conclusions

From the analysis shown in this work, it is quite evident that different sites of Liguria region have very different wind potential characteristics. From the monitored data as well as from their Kriging map, it seems that some internal territories on the mountains as well as some part of the coast in the western side are more promising than others for the exploitation of the wind for energy production. In addition, this potential seems quite stable in the years. However, as usual in these cases, also due to the complex orography of Liguria region, a monitoring campaign on the field should be performed on the site.

From the data obtained on the 25 stations, only 4 of them seem to be eligible for energy production. But, due to other constraints such as environmental protected areas, only Capo Vado seems the only one where the wind potential can be effectively exploited.

Acknowledgment

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